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Coupling of airborne sound into the earth: Frequency dependence

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Simultaneous measurements have been made of sound pressure above the ground and seismic velocity below the ground surface resulting from a source suspended in the air a variable distance from the surface. The ratio of seismic velocity to acoustic sound pressure has been determined; there are peaks in the ratio in the vicinity of 45 and 90 Hz depending on the height of the speaker. The source-receiver distance was 10, 30, and 60 m; the source height was varied between 1 and 10 m. The frequency of maximum acoustic coupling was found to agree well with theory; the first and third shear modes appear to be excited. Results for vertical, horizontal, and radial motion indicate the coupled seismic signal is greatest for vertical, next greatest for radial, and least for transverse, though the difference between radial and vertical displacement velocities was not great and depended on the speaker altitude.

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INTRODUCTION

The coupling of airborne sound into the earth has received only sporadic attention since the pioneering work of Lamb.¹ A series of papers by Press and co-workers²⁻⁵ in the early 1950s did much to explain seismic signals resulting from airborne blasts. They found that airborne blasts typically excited ground vibrations at a frequency such that the dispersive seismic velocity matched the speed of sound in air. The equations for the frequency of maximum coupling to seismic modes were solved for a ground plane composed of two elastic layers and a liquid layer over an elastic solid. Measurements of the sound coupled into a sheet of floating ice agree well with theory. More recent work has been concerned with seismic disturbances resulting from shock waves resulting from supersonic aircraft.⁶⁻⁸ In this case, the effective speed of the disturbance across the earth varies with aircraft speed and direction with respect to the horizontal.

The work reported here was designed to determine the coupling into the earth as a function of frequency in the range 20–300 Hz with varying source-receiver distances and source heights above the surface. The frequency at which maximum coupling occurs will be the subject of this paper; comparison of the magnitude of the seismic signal to theory will require more extensive theoretical work.

I. EXPERIMENT

Two series of measurements were made on the same site at the Waterway Experiment Station at Vicksburg, Mississippi. The test site is relatively flat with a gradual drop in elevation from south to north of approximately 1 m per 100 m. The surface soil is a brown to dark brown heavy, silt loam (CL). The texture of the subsoil ranges from heavy loam (CL) to silty clay loam (CL). Seismic shear and compression velocities were measured using standard seismic refractions techniques.⁹ The seismic survey indicated a surface layer 5.3–6.9 m in depth with a compression wave velocity of 340–350 m/s and a shear wave velocity of 150–160 m/s. The underlying layer had a compression wave velocity between 950 and 2000 m/s. This variation was possibly due to variable water content in the lower layer.

The experimental layout is shown in Fig. 1. Location 2 was not used in the first series of tests. The sound was driven by a large bass-reflex speaker system driven by a 175-W amplifier. Seismic response data were measured using Mark Products L-4A-3D scientific triaxial geophones; these geophones are suspect above 10 Hz. They were buried with approximately 5 cm of soil on top to keep the ground surface smooth. The acoustic sound pressure was measured with broadband capacitance-type microphones. Microphone heights were varied between 0 and 2 m. All signals were recorded

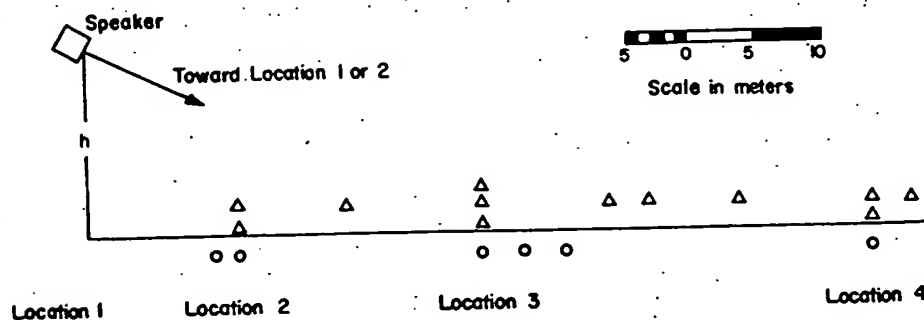


FIG. 1. Test site layout; Δ represents microphones; \circ represents geophones.

on a 14-track FM tape recorder with a frequency response from 0 to 2500 Hz running at $7\frac{1}{2}$ ips. The analog signals were digitized before analyzing the data at a rate of 5000 samples per second. The signal from the source was band-limited pink noise and a swept frequency between 20 and 700 Hz.

The source height was varied by hoisting the speaker with a crane. By suspending the speaker from a single cable, coupling from the speaker through the support into the ground was eliminated.

II. EXPERIMENTAL RESULTS

These measurements provided three separate pieces of information which will be discussed here: the surface impedance of the test site, the ratio of seismic to acoustic signal strength, and the dependence of this ratio on angle of incidence of the incoming wave (speaker height).

The results of surface impedance measurements are presented in Figs. 2(a) and 2(b). Sound amplitudes during test I were made at positions 3 and 4 for microphone heights between 0 and 2 m in 6-in. intervals. For test II, heights of 1 and 2 m were employed. As a result, the first series of measurements yielded more data to be used in determining surface impedance and exhibit less scatter. Impedance values were determined using the theory of Donato.¹⁰ The method used to

extract impedance values from measured amplitude as a function of receiver height and distance is discussed in detail in Ref. 11. The curves in Fig. 2 were computed from the equations developed by Chessell¹² using values of specific flow resistance given in the figures.

The ratio of seismic particle velocity to acoustic sound pressure was termed the coupling coefficient given in units of cm/s per μbar . Results for typical swept frequency tests are presented in Figs. 3(a) and 3(b). For both cases, the speaker was 2.44 m above the surface. Note that for both tests maxima in the coupling coefficient occur near 40 and 90 Hz.

Similar results are given in Fig. 4(a) where excitation was provided by band-limited pink noise (45–90 Hz) centered at 63 Hz. Figure 4(a) gives results for vertical particle seismic velocity, Fig. 4(b) for radial seismic particle velocity. Note that the peaks near 40 and 90 Hz appear for both directions of motion though the peaks in the radial displacement are not quite so large. The radial geophone also shows a lower-frequency coupling coefficient peak; this lower-frequency peak has not been studied in detail. Transverse displacement velocities showed similar frequency dependence with a magnitude lower than that of the radial coupling.

Figures 5(a)–5(e) show the shift in the peak near 50 Hz as a function of speaker height. The frequency axis for these figures is expanded relative to previous fig-

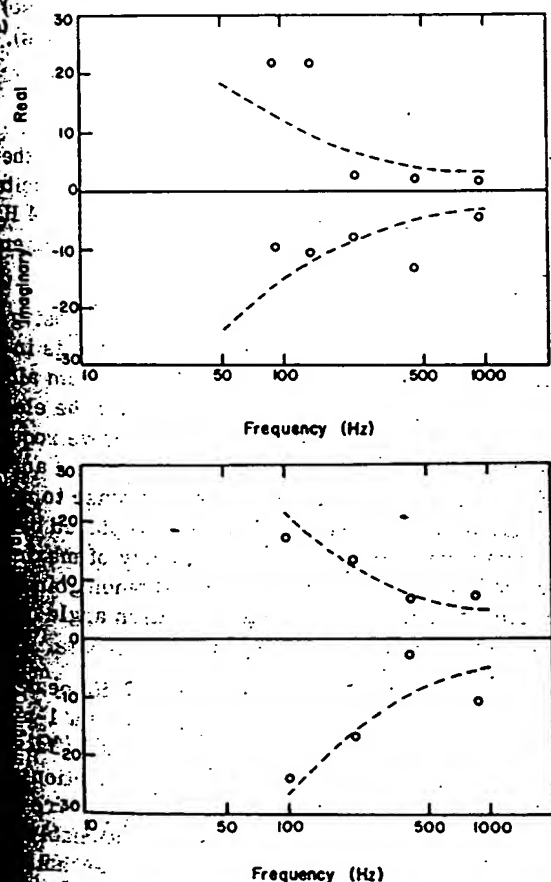


FIG. 2. Normalized surface impedance ($Z/\rho_0 C$); (a) test I; line computed with $\sigma = 300 \text{ g cm}^{-3} \text{ s}^{-4}$ using theory of Donato; (b) test II; dashed line computed with $\sigma = 130$.

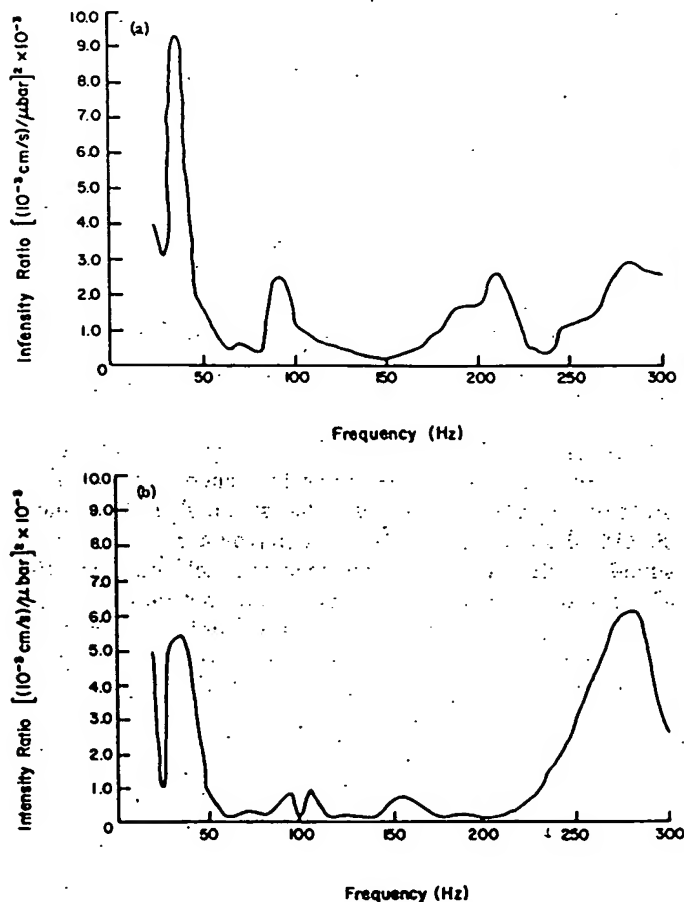


FIG. 3. Seismic/acoustic coupling coefficient for swept frequency; (a) test I; (b) test II.

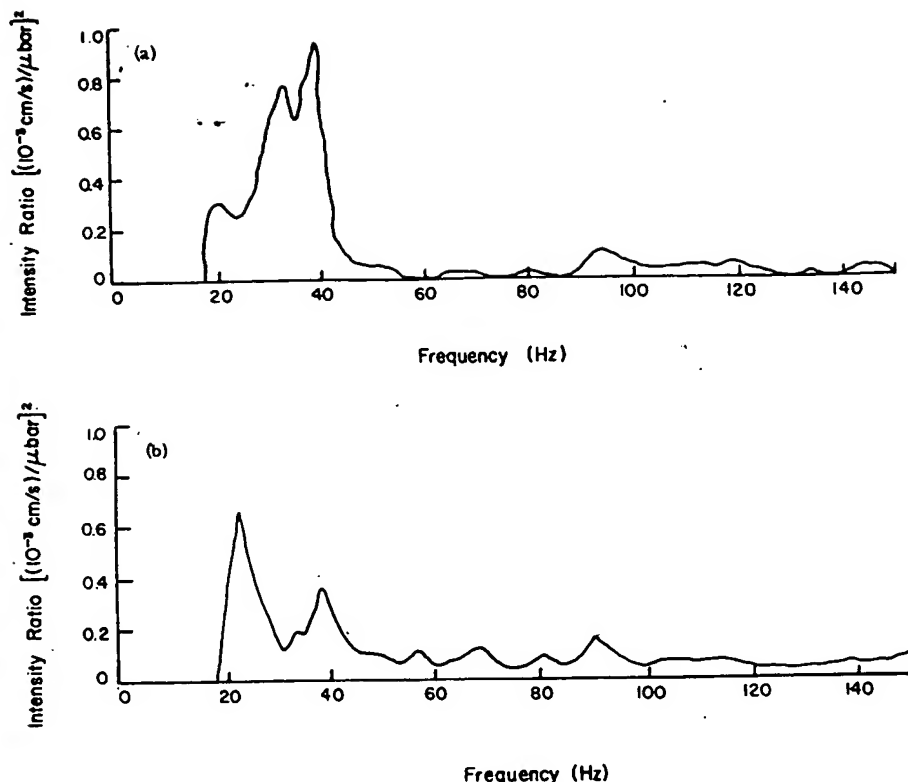


FIG. 4. Seismic/acoustic coupling coefficient for band-limited pink noise (63-Hz octave band); (a) vertical displacement; (b) radial displacement.

ures. Although the peaks in coupling are not so well-defined on the expanded scale, there is a definite (though not uniform) shift in the frequency of maximum coupling as the speaker height is increased from about 57 Hz at a 1-m height to 42 Hz at 10 m. These data were collected at the 10-m position so the nominal angle of incidence varied from 5° at a 1-m height to 45° at 10 m. There is a difference between the frequency of maximum coupling at a speaker height of 2.44 m at the 10-m location as compared to the results presented earlier for the 30-m location. This difference can only partially be attributed to a different layer thickness (5.3 m at location 2, 6.1 m at location 3).

III. DISCUSSION OF RESULTS

The surface impedance measurements suggest that the porous soil has a significant influence on the coupling process even at 40 Hz. The static soil impedance should be about 10^3 greater than ρc for air, but the measured specific surface impedance is much less than 10^3 . The relatively thin porous layer would not be expected to affect the frequency of maximum coupling so much as the amplitude. Since the equations for the amplitude of the waves coupled into the earth have not yet been solved, we can only speculate that the porosity of the surface will affect this amplitude.

The frequency of maximum coupling into the earth can be predicted based on the work of Espinosa, Sierra, and Mickey⁶ for coupling of sound into a waveguide formed by the ~6-m-thick surface layer. Following the notation of Ref. 6, the critical angle for coupling is

$$\sin \phi_c = V_s / V_a, \quad (1)$$

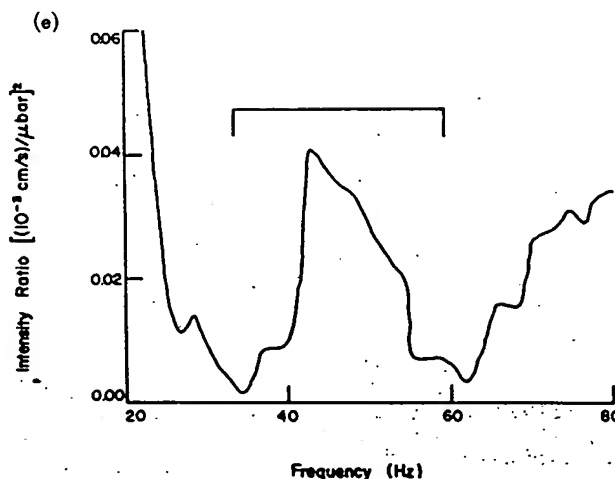
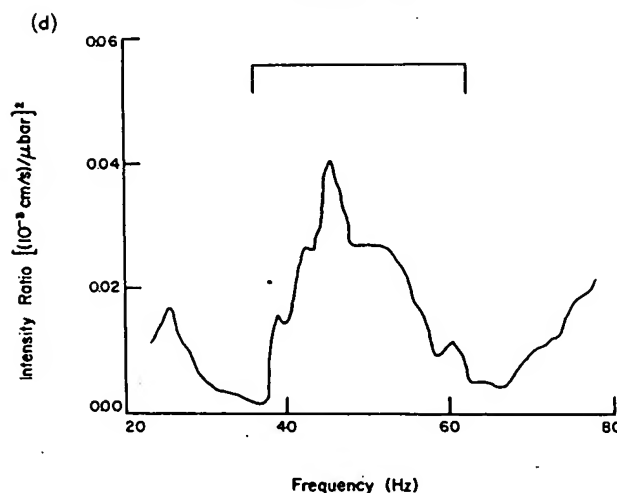
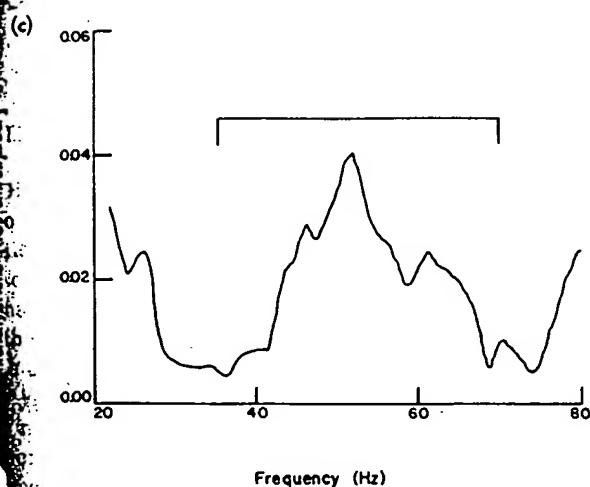
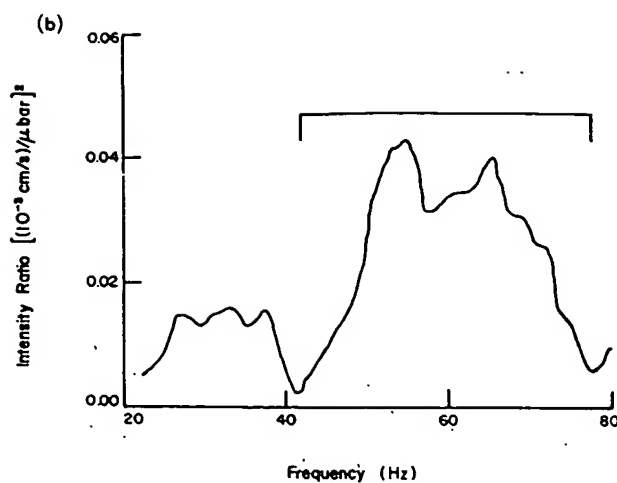
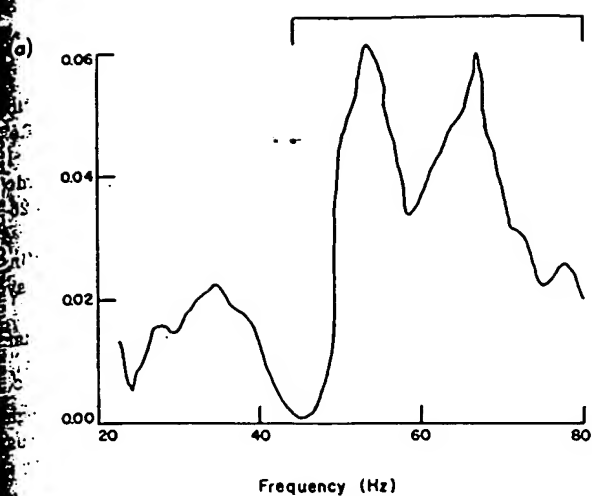
where V_s is the shear velocity (160 m/s for our case) and V_a is the compressional wave velocity (330 m/s). For constructive interference,

$$f_a = (\eta + 1)c / 2H \cos \phi, \quad (2)$$

where H is the thickness of the surface layer, c is the speed of sound in air, and η is the mode number excited. For our case, with $\eta = 0$, $f_a = 32$ Hz; for $\eta = 1$, $f_a = 64$ Hz; and with $\eta = 2$, $f_a = 95$ Hz; the sweep tone measurements show peaks near 32 and 95 Hz.

The effect of speaker height can be estimated using the same approach. As the height of the source is increased, the distance between pressure maximum along the surface will decrease as $\cos \theta$, where θ is the elevation angle. For constructive interference, we require that pressure maxima occur at the same interval across the surface, hence the frequency must decrease to maximize coupling. If c in expression (2) is replaced by $c \cos \theta$, for a given value of η , the frequency of maximum coupling should shift by a factor of 1/1.4 when going from an elevation angle of 5° to an elevation angle of 45°. The measured factor is 1/1.38.

There is also a systematic shift in the 67-Hz peak as the source height is increased: from 67 Hz at a 1-m height to 58 Hz at 10 m. This shift represents a factor of only 1/1.2 suggesting that the simple explanation used for the 50-Hz peak will not suffice. The higher-frequency peaks shown in Fig. 2 do not shift noticeably with elevation angle suggesting a different mechanism for coupling of sound at these frequencies. It is possible that these high-frequency peaks involve a resonance in the geophone; the wavelength is about twice the geophone length.



Seismic/acoustic coupling coefficient for different source heights; test II; (a) 1 m, (b) 2.44 m, (c) 5 m, (d) 7.5 m,

CONCLUSIONS

Frequency of maximum acoustic coupling into the can be understood in terms of excitation of non-surface modes. Although this simple theory provides reasonable agreement with the measured frequency of maximum coupling, it does not include the effects of the upper porous layer. This fact suggests that the

frequency dependence of the coupling is not affected by the porous layer. One cannot conclude, however, that the porous layer does not affect the magnitude of the coupling. Measurements of vertical, radial, and transverse seismic velocities suggest that the ordering of magnitude found in Ref. 8 is reproducible; some change in the relative magnitude of the vertical and radial displacement velocities with nominal angle of incidence was observed.

ACKNOWLEDGMENTS

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